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Precautionary management of Baltic Sea cod (*Gadus morhua callarias*) under different environmental noise and harvesting strategies

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Many cod stocks have decreased during the last decades due to heavy exploitation. One reason is the difficulty to fit complex population dynamics, assessment methods and economic interests together. Moreover, strong environmental fluctuations, such as climate change, affect the success of population management. We consider precautionary harvest strategies in the management of Baltic cod (*Gadus morhua callarias*). We address the following questions: How does the frequency structure in environmental noise affect cod abundance under alternative harvesting strategies? What are the possibilities and limits for precautionary management of Baltic cod? We compare proportional and two threshold harvest strategies. The proportional strategy creates more stable economy while the threshold strategies produce higher sustainable yield and spawning stock biomass, although annual catch may vary substantially.

Introduction

Atlantic cod (*Gadus morhua*) is one of the economically and ecologically most valuable marine fish species in the northern hemisphere (FAO 2001, Poulsen *et al*. 2006). Many cod stocks have decreased drastically since the 1970s, because of their heavy exploitation (Myers *et al*. 1997, Brander 2007a) or due to unfavorable environmental factors (Lilly *et al*. 2008). Population dynamics of exploited stocks are largely determined by the volume of recruitment and harvesting (Myers *et al*. 1995, Jonzen *et al*. 2002). The eastern Baltic Sea cod (*Gadus morhua callarias*) is spatially separate and genetically divergent from the Atlantic cod population (Nissling and Westin 1997, Nielsen *et al*. 2001), and adapted to brackish-water environment (Nissling and Vallin 1996, Wieland and Jarre-Teichmann 1997, Vallin and Nissling 2000).

In the Baltic Sea, the main environmental factors affecting cod distribution and reproductive success are oxygen and salinity (Tomkiewicz *et al*. 1998, Aro 2000, MacKenzie *et al*. 2000). The most favorable conditions for reproduction follow major saline-water inflows (salt pulses) from the North Sea (Westin and Nissling 1991, Heikinheimo 2008). Moreover, cod dynamics are influenced by harvesting intensity (Röckmann 2006, Suuronen *et al*. 2007) and predator–prey relationships (Sparholt 1994, Nissling 2004, Link *et al*. 2009). Also, cannibalism may occur if cod popu-

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lation densities are high (Köster and Möllmann 2000, Uzars and Plikshs 2000, Köster *et al*. 2005).

Baltic cod have been exploited intensively since the early 1950s (Sparholt *et al*. 1994, MacKenzie *et al*. 2000). Nowadays, the International Council for the Exploration of the Sea (ICES) sets annual recommendations for the total allowable catch (TAC) and other precautionary harvesting limits (Brander 2005, ICES 2012: 11). ICES also conducts annual stock assessments and develops recruitment and spawning stock biomass (SSB) estimates, which have been available for the eastern Baltic cod since 1966 (ICES 2012). Conclusive restrictions of harvesting are set by the EU and Russia. Since the implementation of an EU management plan for the Baltic cod stocks, ICES has recommended the fishing mortality (F) of 0.3 to achieve annual MSY (maximum sustainable yield) and TAC (ICES 2012: 11). However, due to economic, social and political reasons, TAC has occasionally been higher as compared with that advised by ICES (Stokke and Coffey 2004, Döring and Egelkraut 2008). Restrictive quotas have also induced discards and fishing of undersize cod (Suuronen *et al*. 2007). The eastern Baltic Sea cod landings had remained at a high level over a decade (around 200 000–400 000 tonnes annually), until the prominent decline in early 1990s (Köster *et al*. 2009, ICES 2012: 11). The stock remained at a low level until a substantial increase in 2006, which resulted from a combination of increased recruitment and management measures (Eero *et al*. 2012). Currently the eastern Baltic Sea cod is harvested at a sustainable level (ICES 2012: 11).

Population dynamics are a result of the interaction between species, environmental conditions and population biology (Begon 1996, Lindén 2010). Climate fluctuations can crucially affect reproductive success and mortality, which consequently change the population size (Steele 1985, Stenseth *et al*. 2002). The population fluctuations mostly have typical autocorrelation structures which can be affected by the characteristics of the environmental noise effect (Kaitala *et al*. 1997, Kaitala and Ranta 2001). Observed low-frequency fluctuations with positive autocorrelation structure are referred to as red noise, fast changing fluctuations with negative autocorrelation as blue noise, and fluctuations with equal mix of frequencies as white noise (Ripa and Lundberg 1996, Ruokolainen *et al*. 2009). In marine environments, fluctuations tend to be dominated by positively autocorrelated low-frequency noise (Steele and Henderson 1984, Kaitala *et al*. 1997, Vasseur and Yodzis 2004), because of the characteristic buffering capacity of the sea (Vasseur and Yodzis 2004). These red noise effects include seawater temperature and prolonged water change in the Baltic Sea.

Using an age-structured model of the Baltic Sea cod under different environmental noise and harvesting strategies, we address the following questions: (1) How does the temporal autocorrelation structure of the environmental noise affect cod abundance? (2) What are the benefits and possible threats of using precautionary (risk avoiding) management (harvest strategy) of the Baltic Sea cod? We use several criteria for describing the risks in the fisheries economics, e.g., mean and variability of yield, probability of low levels of spawning stock, and average fish size. Our aim is not to comment on the current situation in cod management. Instead, we are interested in analyzing how different harvest strategies perform under different environmental fluctuation scenarios.

We compare three harvest strategies: one proportional and two threshold harvest strategies with different threshold limits. Used thresholds were defined based on the SSB limit (B_{lim} = 160 000 tonnes) and precautionary (B_{pa} = 240 000 tonnes) reference points formerly used by ICES (ICES 2005). These threshold values were developed to prevent stock collapses and ensure sustainable fishery management (ICES 2008: 2–4). Precautionary harvesting has been recommended for highly fluctuating fisheries (Kaitala *et al*. 2003). These harvest strategies are expected to reduce the fluctuations in the population dynamics and stabilize the harvest and annual yield.

Material and methods

Cod model

The model of the dynamics of the Baltic cod was based on a simple spawning stock-recruitment Ricker model (Hilborn and Walters 1992). In the model, age structure was specified explicitly. We considered the average salinity affecting the recruitment as an environmental factor (Köster *et al.* 2001, Heikinheimo 2008). We modelled the recruitment of cod applying different environmental noise structures. We use the Ricker stock-recruitment model estimated by Heikinheimo (2008) based on the recruitment 1974–2004. The number of 1-year-old individuals one year after spawning is calculated as follows:

$$N_{t+1,1} = s_0 \mathrm{SSB}_t \exp(a - b\mathrm{SSB}_t + cE_t) \quad (1)$$

where SSB is the spawning stock biomass, s_0 is the survival during the first year, and a, b, and c are the parameters. E_t is the environmental noise with mean 0 and standard deviation 0.33 (e.g. salinity). The parameter values are as follows: a = 7.576, b = 0.001, c = 1.549 (Heikinheimo 2008). The estimated natural mortality of cod at age 0, M_0, varied during the period 1974–2004 between 0.2 and 1.4 (ICES 2005). We used M_0 = 0.7 providing the survival for the first year group s_0 = exp(–0.7) = 0.5.

The age structure dynamics of cod is given as:

$$N_{t+1,i} = N_{t,i-1} \exp(-M_{i-1} - F_{i-1}), \quad (2)$$

where M and F are the natural and fishing mortalities. The natural mortality M was assumed to be 0.2 year^{-1} except for age group 1, where it was assumed to be 0.3 year^{-1} (ICES 2005). For age group 2, the fishing mortality was 0.1F and for age group 3 it was 0.5F (ICES 2005).

The spawning stock biomass is calculated as follows:

$$\mathrm{SSB}_t = \sum_{i=\text{Age at Maturity}}^{\text{MaxAge}} w_i N_{t,i} \,, \quad (3)$$

where the average weights at age, w_i, are: w_2 = 0.166, w_3 = 0.406, w_4 = 0.783, w_5 = 1.189, w_6 = 1.704, w_3 = 2.578, and w_8–w_{13} = 3.826 kg (ICES 2009: 29–40). The maximum age group was taken as MaxAge = 13 years. Age at maturity used in the simulations was 3 years.

The harvestable biomass is considered to be

$$X_t = \sum_{i=2}^{\text{MaxAge}} w_i N_{t,i} \,, \quad (4)$$

The number of individual fish caught in each age group, $C_{t,i}$, was determined according to the following catch equation (Hilborn and Walters 1992):

$$C_{t,i} = N_{t,i}\left(\frac{F_i}{M_i + F_i}\right)\left[1 - \exp\left(-M_i - F_i\right)\right], \quad (5)$$

The biomass harvested from each age group, $Y_{t,i}$, was obtained by multiplying the number of harvested fish by their mean weight:

$$Y_{t,i} = w_i C_{t,i}, \quad (6)$$

The stochastic time series, representing the environmental noise, E, was modelled as an autoregressive (AR) time series. The AR process can be modelled as (Ripa and Lundberg 1996):

$$E_{t+1} = \kappa E_t + \omega_t \sqrt{1-\kappa^2} \,, \quad (7)$$

where ω_t is a normally distributed independent stochastic variable with zero mean and unit variance. The initial value of E for each simulation was a random number drawn from a normal distribution with zero mean and unit variance. Due to the square root term, the variance of E will remain at unity, independent of its autocorrelation (κ). The process produces blue noise when $\kappa < 0$, red noise when $\kappa > 0$, and white noise when $\kappa = 0$. For red noise we used $\kappa = 0.7$ and for blue noise $\kappa = -0.7$.

Harvest strategies

We applied three different harvesting strategies with fishing mortalities F = 0.3, 0.5 and 1 in a fishery under the different environmental fluctuations characterized by their autocorrelation structures (AC). These are blue (AC = –0.7), white (AC = 0) and red (AC = 0.7) environments. Performance of the harvest strategies was measured in several terms: average yield (1000 tonnes), average weight of individual fish in the spawning stock (kg), coefficient of variation of the yield, average spawning stock biomass (1000 tonnes), average weight of fish in the spawning stock and the probability of low spawning stock biomass. We compared the proportional harvest strategy and two versions of the threshold harvest strategies. The proportional harvest strategy removes a fixed fraction of the stock each year whereas under threshold strategies harvesting is ceased if the stock abundance drops below the threshold limits (Lande *et al*. 1995). The threshold strategies can be considered precautionary strategies (Kaitala *et al*. 2003):

1. Proportional harvesting, where the yield Y_t is defined as a constant proportion h of the harvestable biomass removed, that is, $Y_t = hX_t$.
2. Threshold harvesting with two different threshold values. Here a constant proportion of the biomass will be removed when the spawning stock biomass is above a threshold, B_{pa}, that is, $Y_t = hX_t$ when $SSB_t > B_{pa}$, otherwise $Y_t = 0$.

For each harvest strategy, we simulated the fisheries dynamics for 1000 generations and restricted the analysis to the last 400 generations to avoid the impact of initial transients. Each simulation was repeated 500 times. We initiated the numerical simulations of the stock dynamics 1–3 at an exponentially decreasing age distribution given as $N_{t=1, j=1, ..., 13} = \exp[-(j-1)M] \times 10^8$ fish for each age group $j = 1$–13. Normality of the distributions was tested using a Lilliefors test for goodness of fit to a normal distribution (Conover 1980). Boxplots were based on ten simulations of 10 000 time steps. All the simulations and analyses were carried out using MATLAB (ver. 7.0.1.24704 (R14)).

Results

When applying a fishing mortality of $F = 0.3$, the average yield, average weight of fish or average size of spawning stock biomass could not be differentiated between harvesting strategies. However, the quality of environment affected the outcome of harvesting. The average yield and SSB are lowest in the red and highest in the blue environment (Table 1). The average weight of fish and the coefficient of variation of any measure tend to be highest in the red and lowest in the blue environment. With this fishing mortality, moratoria occur rarely and only in the red environment.

Even moderate harvesting has a clear impact on the fish stock. In the absence of harvesting, the spawning stock biomass stabilizes at 1 700 000 tonnes, and the average size of fish in the harvestable population is 1.9 kg. When applying a more intensive fishing mortality of $F = 0.5$, the highest yield is obtained using the Threshold-240 strategy (Table 2 and Fig. 1) and clearly the lowest yield with proportional fishing strategy (Table 2 and Fig. 2), independent of the environment. The coefficient of variation of the yield is highest for the proportional strategy in the red environment, although the CVs and the differences among the harvest strategies decrease when we move from the red environment to the blue one. The spawning stock biomass is highest in the red environment under threshold strategies but lowest for

Table 1. Fishing mortality = 0.3. Coefficients of variation (CV) are given in parentheses.

Blue environment (AC = –0.7)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)	115 (0.15)	115 (0.15)	115 (0.15)
Average weight (kg)	1.17 (0.11)	1.17 (0.11)	1.17 (0.11)
SSB average (1000 tonnes)	752 (0.11)	753 (0.19)	754 (0.15)
Moratorium probability/year	not valid	0	0
White environment (AC = 0)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)	112 (0.23)	113 (0.23)	112 (0.23)
Average weight (kg)	1.18 (0.15)	1.18 (0.15)	1.18 (0.15)
SSB average (1000 tonnes)	742 (0.28)	741 (0.23)	742 (0.32)
Moratorium probability/year	not valid	0	0
Red environment (AC = 0.7)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)	103 (0.47)	105 (0.47)	103 (0.47)
Average weight (kg)	1.19 (0.17)	1.19 (0.17)	1.19 (0.17)
SSB average (1000 tonnes)	682 (0.34)	691 (0.46)	683 (0.47)
Moratorium probability/year	not valid	0.014	0.002

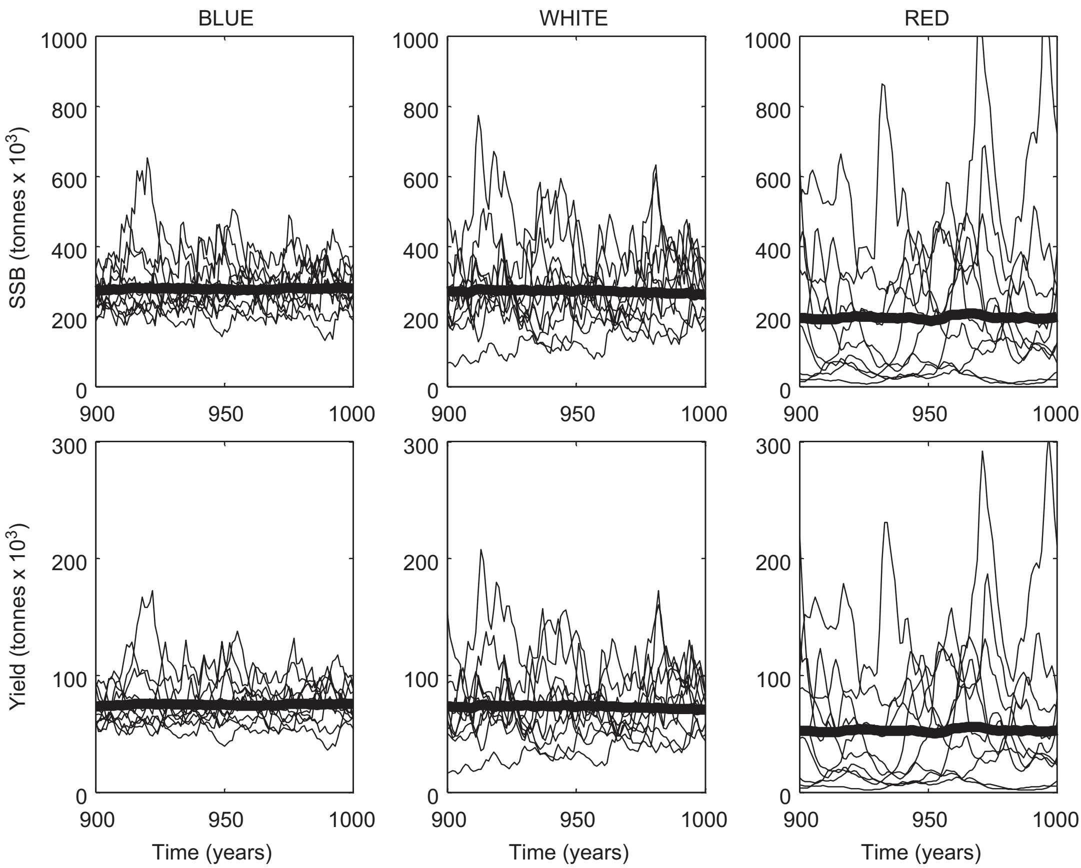

Fig. 1. The SSB and yield of cod during the last 100 years of the timespan of the simulations under proportional harvesting with $F = 0.5$. Ten simulations and their mean values are shown.

Table 2. Fishing mortality = 0.5. Coefficients of variation (CV) are given in parentheses.

Blue environment (AC = –0.7)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)	75 (0.24)	83 (0.27)	75 (0.24)
Average weight (kg)	0.92 (0.11)	0.94 (0.11)	0.91 (0.11)
SSB average (1000 tonnes)	278 (0.24)	319 (0.19)	280 (0.23)
Moratorium probability/year	not valid	0.034	0
White environment (AC = 0)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)	72 (0.37)	87 (0.36)	76 (0.34)
Average weight (kg)	0.93 (0.14)	0.96 (0.14)	0.94 (0.14)
SSB average (1000 tonnes)	264 (0.38)	339 (0.25)	287 (0.32)
Moratorium probability/year	not valid	0.084	0.012
Red environment (AC = 0.7)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)	53 (0.92)	90 (0.61)	79 (0.64)
Average weight (kg)	0.92(0.14)	1.01 (0.18)	0.98 (0.17)
SSB average (1000 tonnes)	200 (0.90)	369 (0.47)	307 (0.55)
Moratorium probability/year	not valid	0.166	0.1

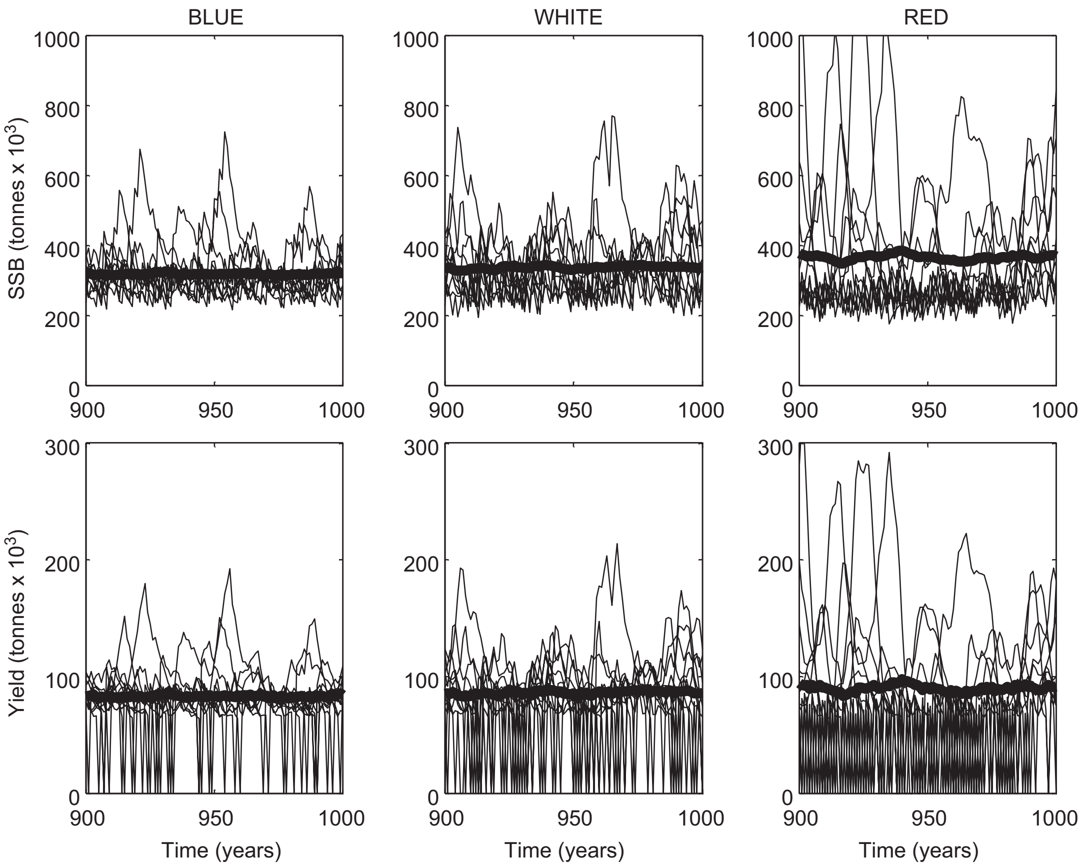

Fig. 2. The SSB and yield of cod during the last 100 years of the timespan of the simulations under Threshold-240 strategy with $F = 0.5$. Ten simulations and their mean values are shown.

the proportional strategy. The threshold strategies maintain higher levels of spawning stock biomass as compared with proportional harvesting, although the difference tends to decrease in the blue environment. The average size of fish is highest in the red environment under threshold strategies decreasing towards the blue environment. The harvest moratoria are common under threshold strategies (Table 2). In the red environment, a change from proportional to threshold strategies decreased the coefficient of variation from 0.92 to 0.61–0.64 (Table 2). Cod stocks tolerate proportional harvesting with fishing mortality $F \leq 0.5$, except in the red environment, where the average value of the stock decreases and its CV increases notably as compared with the white and blue environments (Table 2 and Fig 1). With the threshold harvesting cod stocks remain more constant and there is no imminent collapse risk. Low stock abundance will set the fishery moratoria, until the stock is again above the threshold limit (Fig. 2).

When fishing mortality increases to $F = 1$, stocks will collapse in all environmental scenarios under proportional harvesting. For both threshold strategies, the coefficients of variation are highest in the red environment. Obviously, the probability of moratoria is also higher where $F = 1$ than for the lower fishing mortalities. All other measures (mean values of yield, size of fish and SSB) decrease when compared with lower fishing mortality values (Figs. 1 and 2). Cod stocks will typically collapse within 30 years under proportional harvesting where $F = 1$.

The boxplots, shown for proportional harvesting and Threshold-240 strategy, also indicate that the variability of the SSB's increase with the environment moving from blue to red (Figs. 3

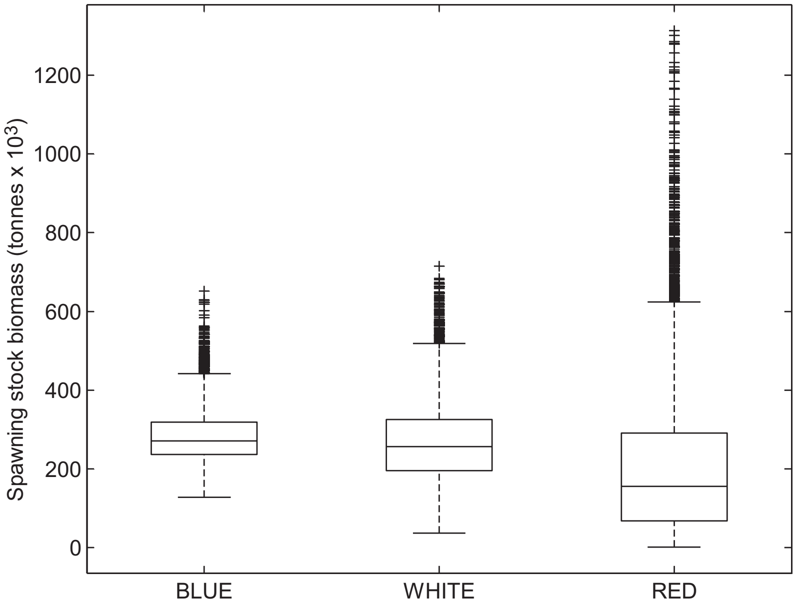

Fig. 3. Boxplots illustrate the variability of the stock dynamics under proportional havesting (F = 0.5) in the blue, white and red environments. The boxes indicate lower quartile, median and upper quartile. The whiskers indicate the minimum and maximum values. '+' are suggested outliers in the data sets.

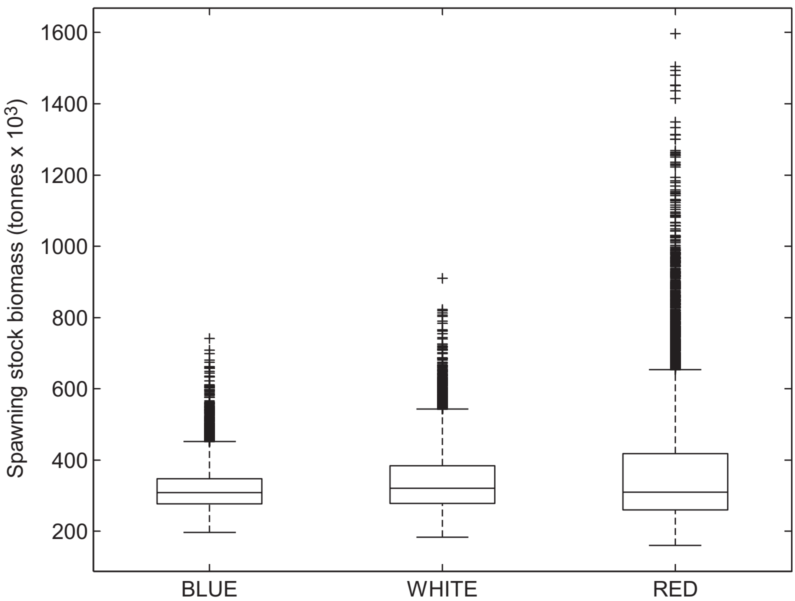

Fig. 4. The variability of the stock dynamics under Threshold-240 strategy (F = 0.5) in the blue, white and red environments. Notation is as in Fig. 3.

and 4). The distributions of the SSB's and yield are highly skewed for all cases included in Tables 1–3 (Lilliefors test for goodness of fit to a normal distribution, $p < 0.05$). The boxplots also suggest a large number of outliers in the data sets. However, we consider these points being a true part of the fluctuations created by the nonlinearities in the stock dynamics and harvesting, and by the interaction of stock dynamics and environmental noise. The deviations between mean and median values are due to the skewedness of the distributions.

Discussion

According to ICES estimations, fishing mortality of the eastern Baltic cod has varied between 0.2

(2008) and 1.5 (2004) during the period 1974–2008. The corresponding spawning stock biomass varied between 66 000 and 697 000 tonnes in 2005 and 1980, respectively. These results verify that with precautionary fishery methods, the Baltic cod stock actually has rather strong resilience. By using precautionary fishery methods it has been possible to permit severe harvesting ($F \geq 1.5$) for a few years. Our results indicate that under stronger environmental fluctuations, especially in the red environment, moratorium frequency increases significantly (Fig. 2), decreasing annual yields, especially during the longer period. While fishing is clearly one of the reasons for population declines, severe natural fluctuations also seem to occur (Eero 2008). The autocorrelation structure of the environmental fluctuations affected the variability of the yield. The variability is clearly highest in the slowly fluctuating red environment. Interestingly, applying threshold strategies does not increase the yield variability. In fact, with the higher ($F = 0.5$) fishing mortality and in the red environment, a change from proportional to threshold strategies decrease coefficient of variation of yield from 0.92 to 0.61–0.64. When fishing mortality increases (F = 1), stocks will become extinct in all environmental scenarios under proportional harvesting. Increased fishing mortality in the threshold strategies decrease the average stock size and the probability of moratoria will increase dramatically. Concurrently the cod SSB, average yields and weights of individual fish will decrease notably (Table 3). The coefficient of variation of yield increased in all scenarios, from 1.01 to 0.89. As a whole, our present study suggests that the traditional use of white noise in designing management methods may need to be replaced by red noise depending on the variable of interest.

Desirable population levels can be most safely maintained by applying threshold harvest strategies. Applying threshold harvest policies increase both the average yield from the fishery and the average size of the fish in the spawning stock. An obvious drawback is that the fishermen need to accept pauses in fishing, that is, moratoria, when the stocks are low. On the other hand, short-time restrictions would produce more long-term benefits (Hall and Mainprize 2004, Tschernij *et al*. 2004), through increased quota of larger fish, which bring better yield quality, and enhancement of stock sustainability.

Salinity is one of the variable environmental factors driving the Baltic cod population dynamics (Westin and Nissling 1991, Aro 2000, Heikinheimo 2008). Climatic and oceanic factors initiate saline-water inflows into the Baltic Sea (Matthäus and Lass 1995, Schinke and Matthäus, 1998) which may be related to the strength of the North Atlantic Oscillation (NAO) (Hänninen *et al*. 2000, Hinrichsen *et al*. 2002). However, the intensity and frequency of large salt pulses have decreased during the last decades

Table 3. Fishing mortality = 1.0. Coefficients of variation (CV) are given in parentheses.

Blue environment (AC = –0.7)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)		78 (0.97)	58 (0.89)
Average weight (kg)		0.90 (0.13)	0.87 (0.13)
SSB average (1000 tonnes)	EXTINCT	250 (0.24)	175 (0.24)
Moratorium probability/year		0.472	0.463
White environment (AC = 0)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)		78 (0.98)	57 (0.90)
Average weight (kg)		0.92 (0.16)	0.89 (0.16)
SSB average (1000 tonnes)	EXTINCT	249 (0.25)	173 (0.26)
Moratorium probability/year		0.479	0.425
Red environment (AC = 0.7)	Proportional	Threshold-240	Threshold-160
Average yield (1000 tonnes)		77 (1.01)	57 (0.94)
Average weight (kg)		0.96 (0.22)	0.92 (0.22)
SSB average (1000 tonnes)	EXTINCT	248 (0.28)	173 (0.30)
Moratorium probability/year		0.480	0.418

(Franck and Matthäus 1992, Heikinheimo 2008). This also means that the salt pulse dynamics have become redder. Similar frequency decelerations (Royer and Fromentin 2007), e.g., in sea temperatures have also been noticed in other sea areas (Rosenzweig *et al*. 2008). On the other hand, over a longer time scale, NAO tends to fluctuate as if it was white noise. Over shorter periods, however, red or blue periods are also possible (Ruokolainen *et al*. 2009). Thus, the observed reddening in the salinity pulses may be a temporary phenomenon. Nevertheless, one potential reason for the current pattern of salinity pulses can be climate change, which presumably will disturb sea ecosystems (Röckmann *et al*. 2007, Rosenzweig *et al*. 2008, Cheung *et al*. 2009) and also modify environmental fluctuations.

Besides environmental factors, also fishery itself can induce fish stock fluctuations (Anderson *et al*. 2008). For example single-species management in multispecies ecosystem has caused stock fluctuations and collapses (Myers 1997, Hjermann *et al*. 2004). It has also been argued that fishery may cause cod to mature earlier as an evolutionary response for the heavy exploitation (Cardinale and Modin 1999, Olsen *et al*. 2004, Vainikka *et al*. 2009), which may have affected annual stock abundances. Because of complex nature of population dynamics, it is challenging to achieve adequate management methods. Stochasticity affects many ecosystem levels but is typically ignored in many ecological models (Clark *et al*. 2001). Among longer living species (e.g., cod), environmental forcing appears often with a delay, why precautionary approaches are necessary (Hutchings and Reynolds 2004, Botsford *et al*. 2011). Main fallacy has been that the management has relied too excessively on insufficient harvesting data (Myers *et al*. 1997, Beddington *et al*. 2007), ignoring the environmental effects to stock dynamics (Myers *et al*. 1995, Hilborn and Litzinger 2009).

The standard stock estimations have been based on single-species stock assessment methods (Cardinale and Arrhenius 2000) and quite narrow scale of estimated parameters (Cook *et al*. 1997). Difficulties to evaluate or forecast the impacts of environmental factors on population dynamics (de Young *et al*. 2004), for example, in the case of climate change, have created a need to develop more accurate management scenarios (Brander 2007b). The consequences of anticipated climate change for the Baltic cod has been studied e.g. by Lindegren *et al*. (2010). They argue that large uncertainties related to the impact of climate change on marine ecosystems have resulted in a lack of reliable predictions in fisheries management. To address this problem they develop an ecosystem-based fisheries management model and study the consequences of climate change on Baltic cod. Climate change is characterized by decreasing trends in salinity. Autocorrelation was estimated from recent data and was found to be 0.66, which is almost identical to our red environment. The scenario with no trend provides an SSB of 200 000 tonnes which corresponds to our results for $F = 0.5$. As a whole, a decrease in the salinity is expected to cause extinctions in less than one hundred years even under precautionary management. Gårdmark *et al*. (2013) attempt to overcome uncertainties by developing a biological ensemble modeling approach, where three single species models, three multispecies models and one foodweb model were compared under same environmental and management conditions. Based on historical data on salinity and temperature, the frequency variation was assumed to be red. Similarly to our model, extinction will occur in two or three models, and decline of the stock in the rest of the models irrespective of the presence or absence of climate change when the fishing mortality is high ($F = 1.08$). Under low fishing mortality ($F = 0.3$) most of the models predict that the stock will increase even under climate change. Although both Lindegren *et al*. (2010) and Gårdmark *et al*. (2013) include the frequency structure of the environment in their models neither of them present explicit results on its role in the management of marine resources.

When comparing the three harvest strategies, it turns out that the threshold strategies provide more sustainable basis for the exploitation of marine resources than proportional strategies. Especially in the red environment, threshold strategies actually result in substantially lower stock variability than does proportional harvesting. Continuous proportional harvesting without thresholds (Idels and Wang 2008) or insufficient, short term management plans increase the stock collapse risk (Myers *et al*. 1997). The reason is the presence of environmental autocorrelation, which cause fluctuations in population dynamics and uncertainty in stock evaluations. At higher fishing mortalities, the threshold harvest strategy tends to provide a higher yield and spawning stock biomass. Under both threshold strategies, the size of the cod is maintained higher and exploitation of cod was overall on a more sustainable level. It should be noted, however, that the difference between all these three strategies diminishes when the fishing mortality is decreased.

We conclude that the proportional harvest strategy is preferable for the economy (fishermen) in the fisheries when overexploitation is avoided, whereas the threshold strategy may be better from the point of view of the species and the ecological community. These results endorse earlier published reports about the fluctuations and link between environment and population dynamics (Spencer 1997, Kaitala *et al*. 1997, Ripa and Lunberg 1998, Vasseur and Yodzis 2004). Unfavorable environmental conditions combined with excessive harvesting have distinct negative impact to fish stocks, which in the future might challenge the whole fishing industry in a drastic way. This research did not involve short term analyses because main focus was set for long term fluctuations. Accordingly, it is advisable to consider temporal and long term harvest strategies in different environmental and population abundance circumstances, to obtain sustainable fishery principles.

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